



WOODS HOLE OCEANOGRAPHIC INSTITUTION

Applied Ocean Physics and Engineering Department

July 16, 2014

Dr. Thomas Drake
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Dear Dr. Drake:

Enclosed is the Final Report for ONR Grant No. N00014-13-1-0197 entitled "Sediment Transport at Density Fronts in Shallow Water," Principal Investigator Dr. David Ralston.

Sincerely,

A handwritten signature in cursive script, reading "Gretchen McManamin", is written below the word "Sincerely,".

Gretchen McManamin
Administrative Assistant to Dr. David Ralston

Enclosure

cc: Administrative Grants Officer
 ✓ Defense Technical Information Office
 Naval Research Laboratory
 Grant and Contract Services (WHOI)
 AOPE Department Office (WHOI)

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Final Report
Sediment transport at density fronts in shallow water:
A Continuation of N00014-08-1-0846

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Award Number: N00014-13-1-0197

LONG-TERM GOALS

The goal of the overall research was to quantify through observations and modeling how density fronts in shallow estuarine flows impact the mobilization, redistribution, trapping, and deposition of suspended sediment. This current award was a continuation of the original YIP award in order to deliver a remaining increment of funds that had not been allocated. The focus of this continuation was to examine how stratification on the tidal flats varies in parameter space as a function of dimensionless numbers.

OBJECTIVES

The objectives of this continuation award were to

- analyze results from a high-resolution, 3-dimensional, finite-volume hydrodynamic model of the Skagit tidal flats to examine processes leading to the creation and destruction of stratification,
- use the Simpson number to represent the balance between tidal straining and tidal mixing to place the physical processes on the tidal flats in a more general context of estuarine and coastal stratification dynamics

APPROACH

The research builds off an extensive observation and modeling field program on the tidal flats of the Skagit River delta. In the field, we measured velocity, stratification, and suspended sediment at high resolution in shallow flows, tracking the evolution of salinity fronts through the tidal cycle. A major field effort occurred in June 2009 on the Skagit Tidal flats in Puget Sound, coordinated with other researchers in the Tidal Flats DRI. Focused observations of the shallow density front and its evolution through the tidal cycle were complemented by a large scale array of moored instruments deployed during the same period (along with Geyer and Traykovski). These observations, along with observations collected by other investigators (Raubenheimer and Elgar) on other parts of the Skagit tidal flats were used to assess the validity of the numerical model results.

In parallel with the observations, we developed a numerical model of the Skagit tidal flats. The model used the Finite Volume Coastal Ocean Model (FVCOM), but was modified to incorporate recent advancements in sediment transport modeling with the Community Sediment Transport Model System

(CSTMS). The unstructured grid of FVCOM allows the model to simulate conditions the Skagit flats with enhanced grid resolution near the observations. The observations were used to calibrate the model and to evaluate how well the model represents sharp salinity gradients at fronts, both across the tidal flats and at lateral fronts coinciding with channel-shoal bathymetry. Collectively, analyses of the observations and model were used to quantify how local frontal processes on scales of 10's to 100's of meters impact retention, redistribution, and export of sediment over tidal flats on scales of kilometers. Model results from simulations of the observation periods in 2009 and idealized tidal and river forcing conditions provide the basis for the analysis of stratification on the tidal flats in this current project. The analysis was done in collaboration with V. Pavel, a recent graduate of the WHOI joint program, and her advisor B. Raubenheimer.

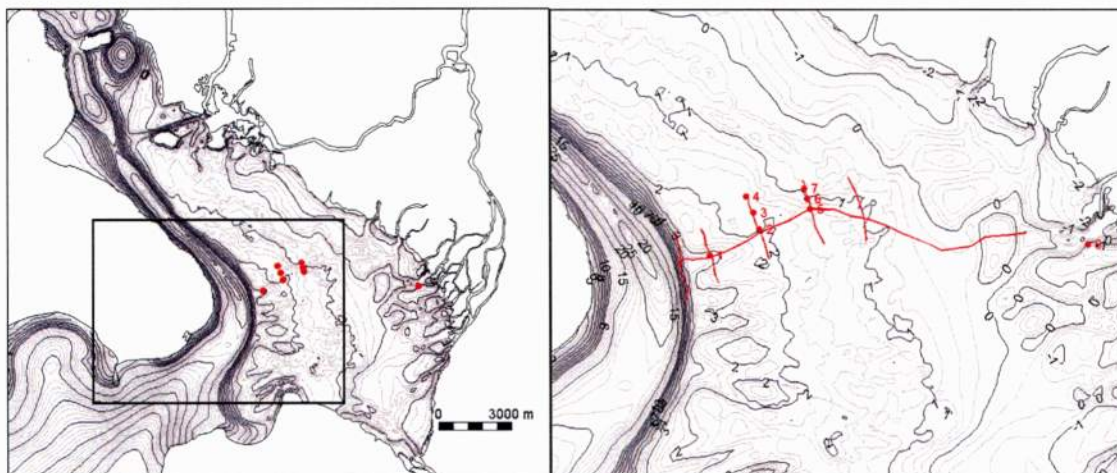


Figure 1. Bathymetry of the Skagit Bay tidal flats (left) with a zoom on the study area on the southern flats (right). Red dots indicate frame locations and lines show across-flats and across-channel survey lines.

WORK COMPLETED

Extensive field efforts and model development occurred under related projects, but here the focus was on assessing the processes governing stratification on the tidal flats (Fig. 2). Data collected during field campaigns on the Skagit tidal flats in 2009 were compared with the model results for those periods. Several manuscripts have been published recently related to this effort. Topics included quantifying impacts of estuarine and fluvial process on sediment fluxes (Ralston et al., 2013), an analyses of generation mechanisms for tidal asymmetries on the tidal flats (Nidzieko and Ralston, 2012), and an evaluation of effects of complex topography on wind correlation length scales and implications for coastal ocean modeling (Raubenheimer et al., 2013).

We also worked on applying to the model results analytical approaches to assess mechanisms of stratification creation and destruction on the tidal flats. This work is in collaboration with V. Pavel, who recently completed her Ph.D. at WHOI working with B. Raubenheimer on stratification dynamics on the Skagit tidal flats based predominantly on field observations. The model provided the opportunity to generalize her observational results to other parts of the tidal flats and to link the Skagit findings to coastal settings with similar forcing regimes.

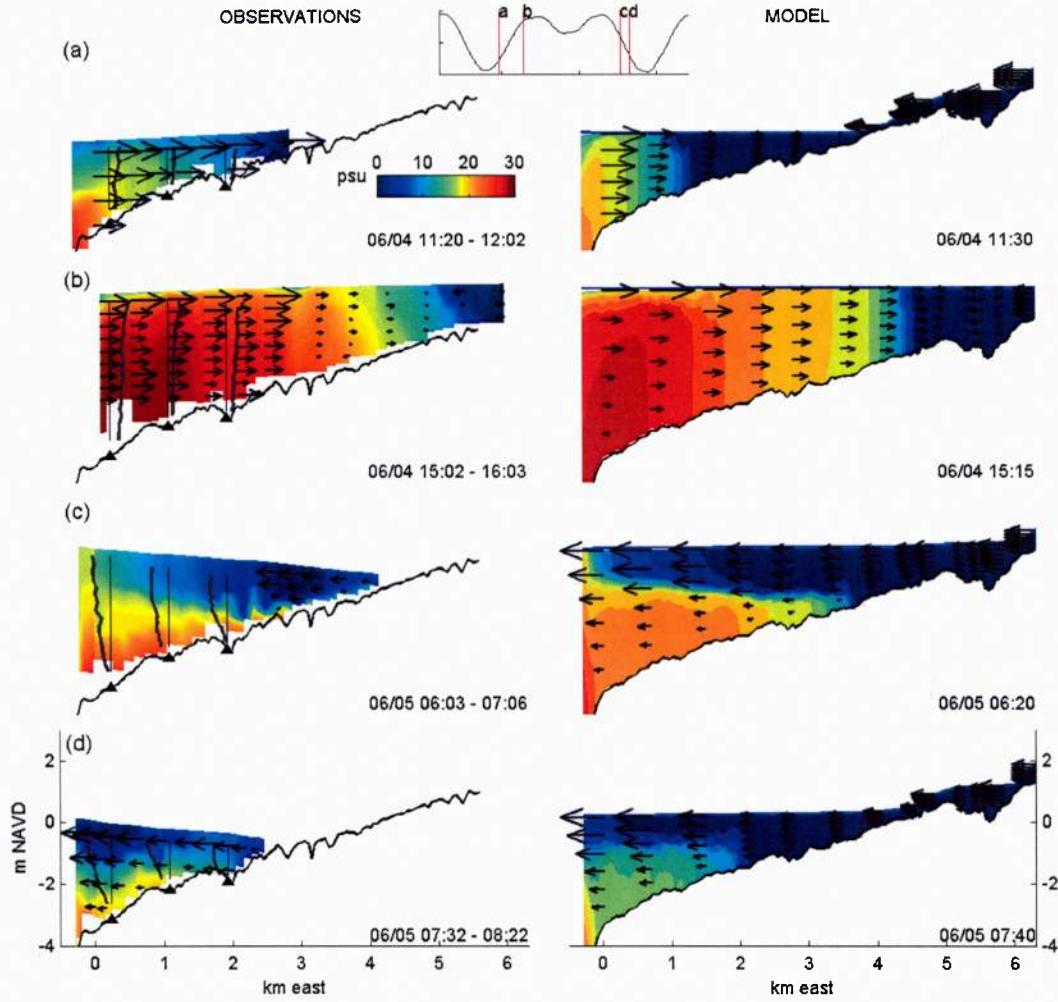


Figure 2. Across-shore transects of salinity on the Skagit flats, from observations (left) and model (right). Top 2 rows are during a flood tide, with a relatively strong horizontal salinity gradient and little stratification in the front; in both the model and observations a near surface layer of fresher water can be seen behind the front. Bottom 2 rows are during an ebb, when stratification was strong even in water as shallow as ~ 1 m. Location of transect is shown in Fig. 1.

RESULTS

From the Skagit model results, we found that the rate of change of stratification, quantified as the integrated potential energy anomaly Φ (Simpson et al. 1990), varied with the Simpson number,

$$Si = \frac{g/\rho_0 \partial \rho / \partial x H^2}{C_d U^3},$$

where g is gravity, $\partial \rho / \partial x$ is the horizontal density gradient, H is the water depth, C_d

is a drag coefficient, and U is the tidal velocity (Fig. 3). The Simpson number represents a dimensionless balance between the creation of stratification by straining of the horizontal density gradient versus destruction of stratification due turbulent mixing associated with tidal bottom stresses (Stacey et al. 2001). These preliminary results were from conditions focused during the period of observations and in the region where instruments were deployed were extend over a longer time series that includes a wider array of forcing conditions, and the model was used to assess how the results varied spatially with mean water depth and proximity to the river mouth. The Skagit results were compared with results from models of other estuaries, including the Hudson, Merrimack, and

Connecticut Rivers, to assess how the stratification and the Simpson number transitions found on the tidal flats fits into estuarine parameters space. The dimensionless number approach demonstrated that the Skagit stratification dynamics were similar to those in the Merrimack River estuary. While the Merrimack is much deeper (~5-10 m) than the intertidal Skagit delta, it also has strong horizontal salinity gradients and tidally asymmetric stratification found in tidal salt wedge estuaries. The results of this analysis were presented with a poster that the Physics of Estuaries and Coastal Seas Conference.

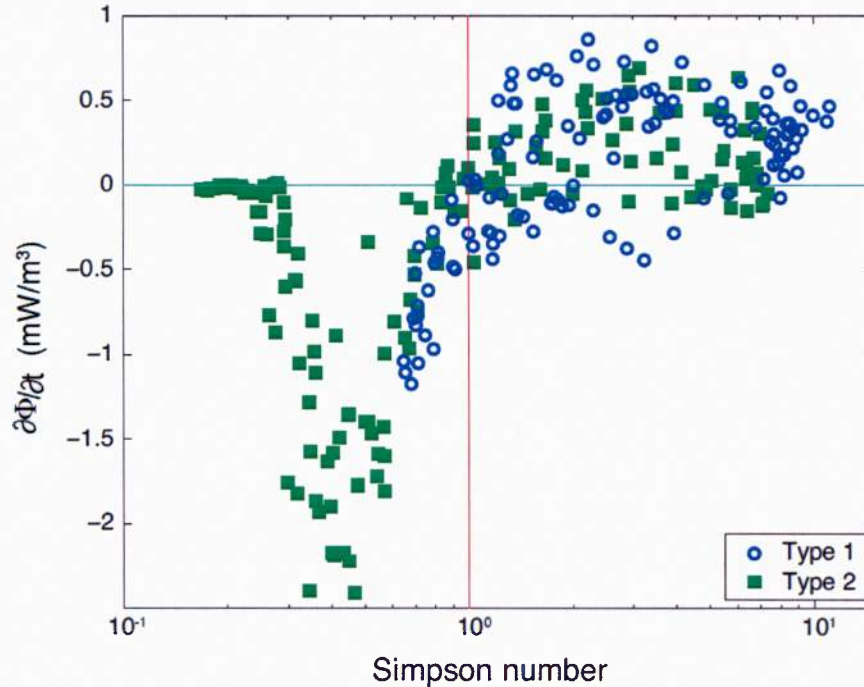


Figure 3. Rate of change of stratification ($\partial\Phi/\partial t$) on the Skagit tidal flats vs. Simpson number, from numerical model results (Pavel, 2012). Type 1 tides are weaker and predominantly semi-diurnal, while Type 2 tides are more energetic and have a greater diurnal component.

IMPACT/APPLICATIONS

Results from this project may be used to enhance hydrodynamic and morphological models of estuaries and deltas, with applications to environmental assessment for the Navy. Trapping and deposition of sediment associated with stratification and density fronts could introduce spatial and temporal variability in bed consolidation and bathymetric relief on tidal flats. The project will also help to evaluate the skill of coastal hydrodynamic models at resolving density fronts and stratification, including the surface expressions that can be assessed with remote sensing.

RELATED PROJECTS

This a continuation of the YIP awarded to Ralston (N00014-08-1-0846), and is closely linked to the Tidal Flats DRI. The field efforts on the Skagit were done in conjunction with Geyer and Traykovski. The model and grid development has been in collaboration with Geoff Cowles. Collaborations with others involved in the DRI include Raubenheimer and Elgar (for bathymetry, observations for model calibration, and use of the model to interpret water column and wind observations), Lerczak (model

simulations at seasonal time scales), Signell and Sherwood (CSTM implementation), and Thomson and Chickadel (bathymetry).

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